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FY92 End of Fiscal Year Letter
01 October 1991 - 30 Sep 1992

ONR CONTRACT INFORMATION

Contract Title: Microstructure and Texture Control of Fatigue in Hydrogen and Marine Environments
Performing Organization: Chemical Engineering and Materials Science
University of Minnesota
Minneapolis, MN 55455
Principal Investigator: William W. Gerberich

Contract Number: N0014-89-J-1726
R & T Project Number: 4311934
ONR Scientific Officer: Dr. George Yoder

A. Scientific Research Goals

It is currently not understood how the anisotropic elastic, plastic and fracture characteristics interact with environment to limit fatigue life in a corrosive medium. This program examines how texture and anisotropic slip character interact in two general classes of BCC iron base and HCP titanium bare alloy systems. Selected area electron channeling, transmission electron microscopy, atomic force microscopy, continuous microindentation and fracture micromechanic methods are being utilized to evaluate microstructural and surface layer effects on environmentally-induced fatigue initiation. In addition, as it is essential to understand the transition from small crack to long crack behavior, additional threshold studies on both Fe-Si and HSLA polycrystals need to be accomplished. In this way, the various stages of nucleation and growth may be combined together for life prediction. The objective is to provide a partial basis for alloy and materials processing design against fatigue in a marine environment.

B. Significant Results

We are now taking a step-wise approach in attempting to understand the corrosion fatigue life of high strength low alloy steels and Ti-6AL-4V. Considerable findings have been made in the low alloy steels.

Two separate studies have been focusing on

- the surface straining and displacements leading to fatigue crack initiation in Fe-Si and HSLA polycrystals;
- the onset of hydrogen-induced cracking as a precursor to long fatigue crack growth.

The elucidation of these two fatigue life phases is extremely important since it is now recognized that the total fatigue life may be made up of at least the following stages:

$$N_{total} = N_i + N_{small} + N_{long}$$

where N_i is the number of cycles to initiation, N_{small} is the number spent growing the crack in the small crack regime to where it will grow as a long crack and N_{long} is the normal number of cycles integrated from the long crack threshold to the critical crack size.

Two significant results this past fiscal year are a theoretical model for determining the number of cycles to initiation and a theoretical model for determining fatigue thresholds in hydrogen. Both of these have some preliminary experimental justification. Regarding fatigue thresholds, we have built upon a brittle-to-ductile transition model where cyclic conditions raise the cyclic flow stress and the emission condition for dislocations (slip). When the slip condition is raised to the Griffith condition, k_{IG}, either transgranular cleavage or brittle intergranular fracture can occur. This defines the threshold condition for fatigue crack nucleation given by

$$\frac{k_{IG}^2/\alpha''}{ln(\Delta K_{th}^{eff}\beta')} \simeq \sigma_{ys}\left(\frac{\Delta K_{th}^{eff^2}}{0.008\sigma_{ys}h_s E}\right)^n$$

Since α'' and β' can be described by a rigorous computer simulation of dislocation arrangements, the distance between major slip band upsets (h_s) may be measured, and the yield strength, modulus and cyclic hardening exponent (σ_{ys}, E, N) are generally known or measureable, ΔK_{th}^{eff} may be calculated. It is proposed here that, once ΔK_{th}^{eff} in hydrogen is known; a first order prediction of both initiation and propagation stages can be made. It is not difficult to demonstrate that a free surface displacement accommodation of a slip step which leads to crack initiation will give a fatigue crack initiation life, N_i, given by

$$N_i = \frac{\Delta K_{th}^{eff^2}}{2\sigma_{ys} E f \Delta\epsilon_p h_s}$$

where f is the fraction of cyclic plastic strain from each cycle going into producing the slip step. Since all of these parameters can be quantified except perhaps f, the latter can be independently checked by measuring slip step heights as a function of cumulative plastic strain with the atomic force microscope. Then, a direct comparison to measured initiation life may be made with no adjustable parameters. The final step would then be to integrate the long crack behavior from ΔK_{th}^{eff} to K_{IC}, the fracture toughness. While none of this seems out of reach at the moment, it is clear that several of the assumptions are far reaching such as α'' and β' from the computer simulation being the same for monotonic and fatigue conditions. Nevertheless, using these theoretical approaches as a guide, the important issues where additional work is necessary should evolve.

C. Future Work

Expectations are that such approaches will lead to a physically-based concept for total fatigue life. In this context, cyclic flow parameters, slip planarity, grain size and environmental susceptibility to crack initiation all become factors. Already we have successfully developed an experimental technique for estimating fatigue initiation life. We have also established that atomic force microscopy (AFM) of smooth bar surfaces is possible and should clarify and verify slip-step aspects of the initiation models. Thus, future work will involve cyclic initiation life measurements, associated electron channeling of plastic strain and surface topography with AFM.

D. List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

W. Zielinski and W. W. Gerberich, "Crack-tip dislocation emission arrangement for equilibrium: Part I - in-situ TEM observations of Fe-2wt % Si, "Acta Metall, Mater., vol. 40, No.11 pp. 2861-2871 (1992).

H. Huang and W.W. Gerberich, ibid. "Part II - comparisons to analytical and computer simulation models, Acta Metall., Mater Vol. 40, pp. 2873-2881 (1992).

P.G. Marsh, W. Zielinski, H. Huang and W.W. Gerberich, ibid. "Part III - application to large applied stress intensities," Acta metall, mater. vol. 40, pp. 2883-2894 (1992).

R.R. Keller, W. Zielinski and W.W. Gerberich, "Fatigue-induced surface versus bulk dislocation arrangements in iron alloys," Scripta Metall. et Mat., 26, pp. 1523-1528 (1992).

Y. Katz, R.R. Keller, H. Huang and W.W. Gerberich, "A dislocation shielding model for the fracture of semibrittle polycrystals," Metall, Trans. A, (in press).

2. non-Refereed Publications and Published Technical Reports

W.W. Gerberich, H. Huang and P.G. Marsh, "Macroscopic and microscopic modelling of hydrogen embrittlement thresholds," in Second workshop on hydrogen effects on materials in propulsion systems, NASA Conf. Publ. 3182, Marshall Space Flight Center, Alabama, pp. 196-203 (1992).

3. Presentations

a. Invited

Invited speaker, "The Effect of Local Dislocation Arrangements on Hydrogen-Induced Cleavage," Parkins Symposium on Fundamental Aspects of Stress Corrosion Cracking, Cincinnati, October 22, 1991 (with P. Marsh and H. Huang).

Invited presentation, "Macroscopic and Microscopic Modeling of Hydrogen Embrittlement Thresholds," NASA 1992 Conference on Advanced earth-to-Orbit Propulsion Technology, George C. Marshall Space Flight Center, May 20, 1992.
Invited speaker, "Electron and Acoustic Probes of Stress Corrosion Cracking Events," Gordon Conference on Corrosion, July 20-24, 1992.

Invited Overview Presentation, "Hydrogen/Plasticity Interactions in Corrosion and Stress Corrosion," International Conference on Corrosion-Deformation Interactions, CD1 92, Fountainebleau, France, October 5-7, 1992.

b. Contributed

With W. Zielinski and R.R. Keller, "Heterogeneous Dislocation Loop Nucleation and Free Surface Effects on Plastic Deformation: An in situ TEM study," LEDS III Conf. Ascona Switzerland, September 1992.

With P.G. Marsh, "Influence of Grain Size and Texture on Fatigue Crack Initiation of HSLA Steel in Hydrogen," TMS Fall meeting, Chicago, November 4, 1992.

4. Books (and sections thereof)

W. W. Gerberich, P.G. Marsh and H. Huang, "The effect of local dislocation arrangements on hydrogen-induced cleavage," in Parkins Symposium on Stress Corrosion Cracking, S. Breummer, ed. TMS-AIME, Warrendale, PA, pp. 191-204 (1992).

P.G. Marsh and W.W. Gerberich, "Stress-corrosion cracking of high-strength steels," in Stress-Corrosion Cracking: Materials Performance and Evaluation, R.H. Jones, ed. ASM International, Metals Park, OH, pp. 63-90 (1992).

W.W. Gerberich, P. Marsh, J. Hoehn, S. Venkataraman and H. Huang, "Hydrogen/Plasticity Interactions in Corrosion Cracking," in Corrosion-Deformation Interactions, CD1 '92, T. Magnin, ed. (in press).

E. List of Honors/Awards

Name of Person Receiving Award	Recipients Institution	Name, Sponsor and Purpose of Award
William W. Gerberich	University of Minnesota	Plenary Lecturers (1 of 4) for Corrosion/Deformation Interactions '92, Sponsored by Electricite de France, CNRS FRAMATOME
William W. Gerberich	University of Minnesota	Board of Governors of the NSF Sponsored Institute for Mechanics and Materials. The purpose of the board is to be an oversight body for the Insitution's educational mission of fostering interdisciplinary research and understanding between the mechanics and materials community

F. Participants (1991-1992)

1. Professor Keijiro Nakasa, Visiting Professor, Hiroshima University, Hiroshima, Japan, has returned to his Department of Mechanical Engineering in Japan. While Professor Nakasa participated in the project, he was on sabbatical funds from his Institute and therefore required no ONR support outside of supplies.

2. Dr. Yosef Katz, former Visiting Professor and now at the Nuclear Research Establishment, Beer Sheva, Israel, returned for a brief visit to finish a paper. This will appear soon in Metall. Trans. A (in press).

3. Mr. Peter Marsh, responsible for the largest part of the electron channeling and fatigue interaction portions of the project is in his third year as a Ph.D. candidate, having passed his pre-lims.

4. Mr. Vitek Zielinski, responsible for much of the electron microscopy (see the first four publications) has returned to Warsaw with an MS degree.

5. Ms. Stefanie Harvey has joined the project to develop atomic force microscopy (AFM) techniques as a measure of fatigue initiation.

6. Dr. Robert Keller returned from a post-Doctoral Fellowship at the University of Erlangen to finish two research papers.

G. Other Sponsored Research (1991-1992)

1. DOE, Basic energy Sciences GRANT DE-FG02-84ER45141, "Micromechanisms of Brittle Fracture: STM, TEM and Electron Channeling Analysis," $87,496 7/1/91-6/30/92 one month summer salary.

2. DOE, Basic Energy Sciences Grant DE-FG02-88ER45337, "A Study of Scale Cracking and its Effect on Oxidation and Hot Corrosion," $39,218 11/1/91-10/31/92, 1/2 month summer salary

3. NSF, Center for Interfacial Engineering (with 19 other P.I.'s) $2,600,000, 10/1/92-9/30/93, support for 1 1/2 graduate students, no summer salary.

4. 3M/DARPA/ONR Grant N/N00014-92-J-1062, "Micromechanics of Interfaces in Metal-Matrix Composites," $50,000 9/1/92-8/30/93 with Professor Kohlstedt, no summer salary.

5. NSF, Center for Plasma Aided Manufacturing, 10/1/92-9/30/93, support for 2 co-advised students (Professors Pfender and Heberlein, Mechanical Engineering) no summer salary.

H. SUMMARY OF FY92 PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/PARTICIPANTS (Number Only)

		ONR	non ONR
a.	Number of Papers Submitted to Referred Journal but not yet published:	4	10
b.	Number of Papers Published in Refereed Journals:	4	5
c.	Number of Books or Chapters Submitted but not yet Published:	1	7
d.	Number of Books or Chapters Published:	2	2
e.	Number of Printed Technical Reports & Non-Referred Papers:	1	-
f.	Number of Patents Filed:	-	1
g.	Number of Patents Granted:	-	-
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	2	2
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	2	9
j.	Honors/Awards/Prizes for Contract/Grant Employees: (selected list attached)	2	(1)shared
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grant:		
	Grad Students: TOTAL	3	8
	Female	1	0
	Minority	0	0
	Post Doc: TOTAL	1	1
	Female	0	0
	Minority	0	0
l.	Number of Female or Minority PIs or CO-PIs		
	New Female	0	1
	Continuing Female	1	0
	New Minority	0	0
	Continuing Minority	0	0

Enclosure (4)

ONR FOREIGN TRAVEL POLICY